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Multiplicity of late-type B stars with HgMn peculiarity*

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ABSTRACT

Context. Observations at various wavelengths of late B-type stars exhibiting strong overabundances of the chemical elements Hg and Mn in their atmospheres indicate that these stars are frequently found in binary and multiple systems.
Aims. We intend to study the multiplicity of this type of chemically peculiar stars, looking for visual companions in the range of angular separation between $0\farcs05$ and $8''$.
Methods. We carried out a survey of 56 stars using diffraction-limited near-infrared imaging with NAOS-CONICA at the VLT.
Results. Thirty-three companion candidates in 24 binaries, three triples, and one quadruple system were detected. Nine companion candidates were found for the first time in this study. Five objects are likely chance projections. The detected companion candidates have K magnitudes between $5\overset{\mathrm{m}}{.}95$ and $18\overset{\mathrm{m}}{.}07$ and angular separations ranging from $<0\farcs05$ to $7\farcs8$, corresponding to linear projected separations of 13.5–1700 AU.
Conclusions. Our study clearly confirms that HgMn stars are frequently members of binary and multiple systems. Taking into account companions found by other techniques, the multiplicity fraction in our sample may be as high as 91%. The membership in binary and multiple systems seems to be a key point to understanding the abundance patterns in these stars.

Key words. stars: binaries: close – stars: chemically peculiar – techniques: high angular resolution

1. Introduction

Chemically peculiar (CP) stars are main-sequence A and B type stars in the spectra of which lines of some elements are abnormally strong or weak. The class of CP stars is roughly represented by three subclasses: the magnetic Ap and Bp stars, the metallic-line Am stars, and the HgMn stars, which are late B-type stars showing extreme overabundances of Hg (up to 6 dex) and/or Mn (up to 3 dex).

About 150 stars with HgMn peculiarity are currently known (Renson & Manfroid 2009). Most of them are rather young objects found in young associations such as Sco-Cen, Orion OB1, or Auriga OB1. In contrast to classical Bp and Ap stars with large-scale organized magnetic fields, HgMn stars generally do not show overabundances of rare earth elements, but exhibit strong overabundances of heavy elements such as W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, or Bi. Another important distinctive feature of these stars is their slow rotation ($\langle v \sin i \rangle \approx 29\,\mathrm{km\,s^{-1}}$, Abt et al. 1972). The number of HgMn stars decreases sharply with increasing rotational velocity (Wolff & Wolff 1974). Evidence that stellar rotation does affect abundance anomalies in HgMn stars is provided by the rather sharp cutoff in these anomalies at a projected rotational velocity of 70–80 $\mathrm{km\,s^{-1}}$ (Hubrig & Mathys 1996).

The mechanisms responsible for the development of the chemical anomalies of HgMn stars are not yet fully understood. The abundance patterns may however be connected with binarity and multiplicity. More than 2/3 of the HgMn stars are known to belong to spectroscopic binaries (Hubrig & Mathys 1995).

Over the past few years, we have been involved in extensive spectroscopic studies of upper main-sequence spectroscopic binaries with late B-type primaries with the goal of understanding why the vast majority of these stars exhibit in their atmospheres certain chemical abundance anomalies. Moreover, elements with anomalous abundances are distributed inhomogeneously over the stellar surface (e.g., Adelman et al. 2002; Hubrig et al. 2006). For α And, secular evolution was found for Hg by Kochukhov et al. (2007), while a dynamical evolution of Ti, Sr, and Y spots within two months was reported by Briquet et al. (2010) for the spectroscopic binary HD 11753. Since a number of HgMn stars in binary systems is found at the zero age main-sequence (ZAMS; e.g., Nordstrom & Johansen 1994; González et al. 2006), it is very likely that the timescale for developing a HgMn peculiarity is very short.

Quite a number of HgMn stars belong to triple or even quadruple systems (Cole et al. 1992; Isobe 1991). Out of 30 SB HgMn stars observed with speckle interferometry, 15 appear to have more than two components. Indirect evidence of a third component was found in four other HgMn SBs (HD 11905, HD 34364, HD 78316, and HD 141556) on the basis of spectroscopic and photometric arguments.

* Based on observations obtained at the European Southern Observatory, Paranal, Chile (ESO programme Nos. 074.D-0374 and 076.C-0170).

Additional evidence that other HgMn stars are frequently members of multiple systems is inferred from the results of the ROSAT all-sky survey. X-ray emission was detected by this survey in twelve HgMn stars (seven SB1s, three SB2s, and two for which no radial velocity data are available; Berghöfer et al. 1996, Hubrig & Berghöfer 1998). Previous X-ray observations with the Einstein Observatory and theoretical estimates had suggested that stars in the spectral range B2–A7 are devoid of any significant X-ray emission. In most cases when emission had been detected in these stars, it was found to originate in a cool companion. This suggests that the X-ray emission found in HgMn SBs does not originate in the HgMn primary. From observations investigating late-B type stars with X-ray emission using the ESO 3.6-m telescope with ADONIS, Hubrig et al. (2001) found faint companions to four HgMn stars that were part of the X-ray selected late-B type stars observed, strengthening this interpretation.

In the following, we report the results of our multiplicity study of this class of objects using NACO K-band imaging.

2. Observations and data reduction

We carried out observations of 56 HgMn stars with NAOS-CONICA (NACO; Lenzen et al. 2003; Rousset et al. 2003) on the VLT in service mode between October 2004 and March 2005, and again between November 2005 and February 2006. We used the S13 camera of NACO, which provides the smallest available pixel scale of 13.3 milliarcsec and a field-of-view of 13.″6. All data were collected through a Ks filter in image autojitter mode, where the object is observed at typically 20 different image positions with random offsets between them. Since all our sources are bright in V, we used the visible wavefront sensor of NAOS.

The observed sample was mainly selected from the "Catalogue and Bibliography of Mn-Hg Stars" (Schneider 1981) taking into account accessibility from the VLT. A few targets not listed in this catalogue were selected on the basis of previous spectroscopic studies of late B-type stars, in which HgMn peculiarity was detected. The sample is listed in Table 1. In Col. 1, we give the HD number of the objects, in Col. 2 another identifier, in Cols. 3 and 4 the magnitudes in V and K bands, in Col. 5 the spectral type, and finally in Col. 6 the parallax. All information was collected from the SIMBAD database.

The data reduction was performed with the eclipse package in the standard way. Sky background frames obtained from median averaging of the jittered frames were subtracted from the individual frames. All frames were then flat-fielded and corrected for bad pixels using calibration files provided by ESO.

Astrometry and relative photometry of the multiple systems were performed using the IRAF package DAOPHOT. We assume that systematics introduced are $1/10^{\text{th}}$ of a pixel for the position of the individual objects and 1% for the flux ratio, which we used unless the errors determined by IRAF were higher, generally for the faintest companion candidates. The final errors in the relative positions are estimated by combining quadratically the rms variations in our astrometric analysis with the uncertainty in the plate scale (13.26±0.03 mas) and detector orientation (±0.5°), both provided by Masciadri et al. (2003).

3. Results

We found in total 24 binaries, three triple systems, and one quadruple system in our survey. Out of the 33 companion candidates, we infer that five are chance projections. Nine companion candidates were detected for the first time. The astrometric and photometric results are presented in Table 2 for all multiple systems of our sample. In Col. 1, we list the HD number for each system as well as the pair designation for the higher order systems, and Col. 2 gives the modified Julian date for the observations. In Cols. 3, 4, and 5, we show the separation, position angle, and magnitude difference in the K band between the components, as retrieved by aperture photometry from our images. In Col. 6, we give the K band magnitude for the whole system, as derived from the 2MASS or DENIS catalogues, and in Cols. 7 and 8 we give K band magnitudes for the primary and secondary component, as determined from Cols. 5 and 6. Column 9 lists finally the chance projection probability of the secondary component, as described in Sect. 3.2. An asterisk preceding the HD number in Col. 1 indicates systems where the companion was known before our study. For the two companion candidates that we find within the point spread function, we provide only rough astrometric and photometric estimates.

The images of the resolved binaries are shown in the two parts of Fig. 1. The triple systems can be found in Fig. 2 and the quadruple system in Fig. 3. All images are displayed using a logarithmic scale. In the images with the closest companion candidates, showing just the inner 1″, this logarithmic scale had to be adapted to enhance the image details. The same modification was applied to HD 33904.

3.1. Limits for undetected companions and completeness

The detection limits were computed using the method described in Correia et al. (2006). At each radial distance and position angle from the star, the standard deviation in the flux was calculated over a circular region of radius 70 mas, i.e., equivalent to the mean size of the point spread function (PSF) core. The detection limit as a function of separation from the star is the average of the 5σ flux over all position angles except those lying in the direction of the companion candidate.

For any given component of the binaries as well as for the unresolved sources, we thus have the limiting flux ratio for undetected companions as a function of separation. We can therefore produce a completeness map for each of these sources, i.e. a map giving the probability of detecting a companion as a function of separation and magnitude difference. The total completeness map of all sources is simply the average of all individual completeness maps.

Figure 4 shows the total completeness map. The lines represent the completeness of our observations at levels 99%, 90%, 70%, 50%, 30%, 10%, and 1% completeness, from top to bottom. The circles represent the binaries found in our study. The majority of the companion candidates falls above the 99% completeness level and three more fall above the 90% completeness level. The two sources below 70% are very close to the first Airy ring, where our method is probably very inaccurate. Overall, we are confident in the completeness levels. We note that we plotted only objects with chance projection probabilities below 1% and do not show the objects with separations below 0.″1. Assuming

Table 1. Objects studied in the program.

HD number	Other Identifier	V	K[a]	Spectral Type	Parallax [mas]
1909	HR 89	6.56	6.66	B9IVmn	5.13±0.83
7374	HR 364	5.96	6.21	B8III	6.52±0.79
11753	HR 558	5.11	5.17	A3V	10.55±0.69
14228	HR 674	3.55		B8IV-V	21.06±0.61
19400	HR 939	5.50		B8III/IV	6.21±0.50
21933	HR 1079	5.75	5.88	B9IV	9.18±0.87
23950	HR 1185	6.07	5.98	B8III	10.14±0.90
27295	HR 1339	5.49	5.61	B9IV	12.20±0.76
27376	HR 1347	3.55		B9V	18.27±0.55
28217	HR 1402	5.87	5.64	B8IV	6.70±0.96
29589	HR 1484	5.45	5.66	B8IV	9.46±0.78
31373	HR 1576	5.79	5.97	B9V	7.71±0.87
32964	HR 1657	5.10	5.20	B9V+...	11.65±0.73
33647	HR 1690	6.67	6.86	B9Vn	2.03±1.04
33904	HR 1702	3.28		B9IV&...	17.69±0.71
34364	HR 1728	6.14	6.27	B9.5V	8.20±0.78
34880	HR 1759	6.41		B8III	4.80±1.32
35548	HR 1800	6.56	6.60	B9sp...	4.42±0.80
36881	HR 1883	5.63	4.96	B9IIImnp...	2.23±0.82
37752	HR 1951	6.58	6.71	B8p	4.64±0.96
38478	HR 1985	5.99	6.13	B8IIImnp...	3.71±0.91
42657	HR 2202	6.20	6.33	B9mnp...	5.52±1.09
49606	HR 2519	5.87	6.15	B7III	3.52±0.83
51688	HR 2605	6.39	6.64	B8III	2.72±0.88
53244	HR 2657	4.10	4.37	B8II	8.11±0.63
53929	HR 2676	6.09	6.37	B9.5III	4.60±0.78
59067	HR 2859	5.87	3.75	A0[b]	3.23±1.39
63975	HR 3059	5.13	5.37	B8II	7.76±1.02
65949	CD-60 1951	8.37	8.37	B8/B9	3.60±2.72
65950	CD-60 1952	6.87	6.76	B8III	2.91±0.57
66259	CD-60 1998	8.33		B9.5V	2.91±0.57[c]
66409	CD-60 2009	8.41	8.33	B8IV/V	2.91±0.57[c]
68099	HR 3201	6.08	6.35	B6III	3.74±0.99
68826	AO Vel	9.42	9.11	B9III	[d]
70235	HR 3273	6.43	6.59	B8Ib/II	4.00±0.58
71066	HR 3302	5.62	5.84	A0IVmn	8.25±0.48
71833	HR 3345	6.67	6.78	B8II	2.43±0.82
72208	HR 3361	6.83	6.83	B9p...	4.96±1.04
73340	HR 3413	5.78	6.04	B8p...	6.99±0.44
75333	HR 3500	5.31		B9mnp...	7.45±0.74
78316	HR 3623	5.24	5.46	B8IIImnp	6.74±0.91
90264	HR 4089	4.95	5.31	B8V	7.59±0.50
101189	HR 4487	5.14	5.13	B9IV	10.98±0.57
110073	HR 4817	4.63	4.79	B8II/III	9.19±0.85
120709[e]	HR 5210	4.56		B5III	10.96±0.88
124740	CD-40 8541	7.86	7.83	Ap...	4.86±1.13
129174	HR 5475	4.91		B9p+...	10.28±0.91
141556	HR 5883	3.96		B9IV	15.86±0.84
144661	HR 5998	6.32	6.43	B8IV/V	8.50±0.84
144844	HR 6003	5.86	5.71	B9V	7.65±0.77
158704	HR 6520	6.06	6.15	B9II/III	7.47±1.10
165493	HR 6759	6.15		B7.5II	4.00±1.01
178065	HR 7245	6.56	6.35	B9III	4.34±0.88
216494	HR 8704	5.78	5.93	B8IV/V	4.96±0.84
221507	HR 8937	4.37	4.61	B9.5IVmnpe...	18.28±0.80
224926	HR 9087	5.12	5.44	B7III-IV	7.98±0.71
41040[f]	HR 2130	5.14	5.36	B8III	3.05±0.96

Remarks:
[a]Please note that for some targets, SIMBAD is not listing a K magnitude.
[b]SIMBAD is listing a spectral type G8Ib-II+... for HD 59067. We adopted the spectral type given by Schneider (1981).
[c]HD 65949, HD 65950, HD 66259, and HD 66409 are all members of the open cluster NGC 2516. Since SIMBAD does not provide an individual parallax, we adopted the parallax of the brighter star HD 65950 for HD 66259 and HD 66409.
[d]González et al. (2006) give a distance of 0.72 kpc for HD 68826 (AO Vel).
[e]HD 120709 belongs to the subgroup of PGa stars, which are usually considered as the hotter extension of HgMn stars, exhibiting deficient He and strongly overabundant P and Ga (e.g. Castelli et al. 1997).
[f]HD 41040 is not known to present spectral peculiarities, but the orbital parameters of the short period subsystem are in the range of those typical for HgMn stars. It is not included in the sample of 56 HgMn stars for statistical considerations.

Table 2. Astrometric and photometric results of the candidate binaries and multiples resolved in our study.

HD number	MJD	Separation [″]	Position angle [°]	K mag difference	K mag system	K mag primary	K mag secondary	Projected linear separation [AU]	Chance projection probability [%]
				Binaries					
21933	53376.06	0.124±0.003	112.2± 1.7	2.43±0.01	5.88±0.02	5.99±0.02	8.42±0.04	13.5± 1.3	4.24×10^{-6}
21933	53700.14	0.149±0.003	111.9± 1.4	2.70±0.01	5.88±0.02	5.97±0.02	8.66±0.04	16.2± 1.6	6.19×10^{-6}
*27376	53690.21	5.384±0.003	162.2± 0.5	6.21±0.03	3.95±0.24	3.96±0.24	10.17±0.27	294.7± 8.9	4.83×10^{-2}
*28217	53409.04	0.119±0.004	27.3± 1.8	1.24±0.01	5.64±0.02	5.94±0.03	7.19±0.05	17.8± 2.6	3.96×10^{-6}
*32964	53286.35	1.599±0.004	308.3± 0.5	3.82±0.01	5.20±0.02	5.23±0.02	9.05±0.05	137.3± 8.6	2.84×10^{-3}
*33647	53347.21	0.147±0.003	345.1± 1.4	0.79±0.01	6.86±0.02	7.29±0.03	8.07±0.05	72.4± 37.1	1.80×10^{-5}
33904	53374.17	0.352±0.003	250.9± 0.7	3.29±0.01	3.52±0.24	3.58±0.24	6.86±0.26	19.9± 0.8	3.43×10^{-5}
*35548	53380.15	0.300±0.003	174.1± 0.7	0.76±0.01	6.60±0.02	7.04±0.03	7.80±0.05	67.9± 12.3	2.50×10^{-5}
*36881	53348.22	2.801±0.003	351.9± 0.5	4.16±0.01	4.96±0.02	4.98±0.02	9.14±0.05	1256.1±461.9	1.74×10^{-2}
*42657	53741.18	0.688±0.003	202.9± 0.6	1.45±0.01	6.33±0.03	6.58±0.03	8.03±0.06	124.6± 24.6	5.26×10^{-4}
53244	53408.14	0.332±0.004	114.8± 0.8	4.26±0.01	4.37±0.04	4.39±0.04	8.65±0.06	40.9± 3.2	1.84×10^{-4}
53929	53408.17	3.659±0.003	345.5± 0.5	3.76±0.01	6.37±0.02	6.40±0.02	10.16±0.04	795.4±134.9	7.44×10^{-2}
*59067	53379.26	0.811±0.003	170.4± 0.5	3.56±0.01	3.75±0.04	3.79±0.04	7.34±0.06	251.1±108.1	3.65×10^{-4}
72208	53404.25	0.671±0.004	332.1± 0.6	6.24±0.02	6.83±0.03	6.84±0.03	13.08±0.06	135.3± 28.4	6.12×10^{-3}
*73340	53404.28	0.566±0.004	219.7± 0.6	2.38±0.01	6.04±0.02	6.16±0.02	8.54±0.05	81.0± 5.1	8.90×10^{-4}
*75333	53379.30	1.316±0.003	167.5± 0.5	3.79±0.01	5.44±0.02	5.47±0.02	9.26±0.05	176.6± 17.6	4.81×10^{-4}
*78316	53380.29	0.269±0.003	109.7± 0.9	2.55±0.01	5.46±0.02	5.56±0.03	8.11±0.05	39.9± 5.4	6.01×10^{-5}
90264	53779.20	2.219±0.003	350.2± 0.5	5.51±0.01	5.31±0.02	5.32±0.02	10.83±0.05	292.4± 19.3	6.70×10^{-2}
101189	53403.37	0.337±0.003	104.1± 0.7	1.78±0.01	5.13±0.02	5.32±0.03	7.10±0.05	30.7± 1.6	2.84×10^{-4}
*110073	53404.31	1.202±0.003	73.9± 0.5	3.12±0.01	4.78±0.02	4.84±0.02	7.96±0.04	130.8± 12.1	8.03×10^{-4}
*120709	53404.34	7.830±0.003	105.5± 0.5	1.55±0.01	4.97±0.03	4.97±0.03	6.52±0.04	714.4± 57.4	3.41×10^{-2}
*129174	53404.40	5.537±0.003	110.5± 0.5	0.27±0.01	5.05±0.02	5.67±0.03	5.95±0.05	538.6± 47.7	8.52×10^{-3}
*165493	53442.37	4.041±0.003	257.4± 0.5	2.96±0.01	6.33±0.02	6.40±0.02	9.36±0.05	1010.3±255.1	8.62×10^{-2}
*216494	53298.09	0.069±0.003	285.9± 2.8	0.35±0.01	5.93±0.02	6.52±0.03	6.87±0.06	13.9± 2.4	1.31×10^{-6}
221507	53296.63	0.641±0.004	240.2± 0.6	2.75±0.01	4.61±0.03	4.69±0.03	7.44±0.05	35.1± 1.6	1.14×10^{-4}
*41040	53348.25	<0.05	233.6±10.0	∼0.01	5.36±0.02			<16	5.71×10^{-9}
				Triple systems					
*34880AB	53379.17	0.511±0.003	199.6± 0.6	2.25±0.01	6.43±0.02	6.56±0.02	8.82±0.05	106.5± 29.3	3.62×10^{-4}
*34880AC		4.571±0.007	284.9± 0.5	2.92±0.01			9.48±0.03	952.3±261.9	4.64×10^{-2}
*158704AB	53442.34	0.434±0.003	192.9± 0.7	1.16±0.01	6.15±0.02	6.47±0.02	7.64±0.03	58.1± 8.6	1.26×10^{-3}
158704AC		1.637±0.004	123.6± 0.6	6.18±0.03			12.65±0.03	219.1± 32.3	2.33
178065AB	53286.01	6.427±0.004	204.1± 0.5	6.90±0.02	6.35±0.02	6.35±0.02	13.25±0.03	1480.9±300.3	16.7
178065AC		3.319±0.004	64.9± 0.5	8.96±0.07			15.31±0.05	764.7±155.1	>16.7
				Quadruple system					
66259AB	53731.35	<0.05	2.5±10.0	∼0.04	8.25±0.09			<17	7.00×10^{-7}
66259AC		4.861±0.006	110.8± 0.5	8.18±0.08			17.16±0.11	1670.4±327.2	>5.60
66259CD		0.415±0.013	65.9± 1.8	0.90±0.02			18.07±0.12	142.6± 28.0	>6.29

that both the distribution of separation and the distribution of flux ratio of companions are flat (which is obviously a very rough assumption), we estimate that the completeness is above 90% for separations of a) between 0.″2 and 0.″4 and above a flux ratio of 10^{-1}, b) between 0.″4 and 0.″7 and above a flux ratio of 10^{-2}, and c) between 0.″7 and 8″ and above a flux ratio of 2×10^{-3}. It should be noted that the S13 camera of NACO does not allow to detect companions at large separations (>∼7–8″).

For HD 41040 and HD 66259, we claim companion candidates within the diffraction limit, which are essentially elongations of the PSF. In both cases, we carefully analyzed not only the combined images, but also the individual frames, and were convinced that the results are real. For HD 66259, this is supported by the two PSFs of the other companion candidates in the image not displaying this elongation.

For HD 29589 and HD 31373, we find hints for companions directly on the Airy ring, which we consider as artifacts.

3.2. Chance projections

To identify the systems whose components are gravitationally bound and those that are only the result of a chance projection, we used a statistical approach (see e.g. Correia et al. 2006). In a first step, we determined the local surface density of background/foreground sources in each field. For this purpose, we compiled the number of 2MASS objects brighter than the companion candidates in the K-band in a $30'\times30'$ field surrounding each primary. This leads to the average surface density of objects brighter than the limiting magnitude $\Sigma(K < K_{\rm comp})$. Assuming a random uniform distribution of unrelated objects across the field, the resulting probability $P(\Sigma,\Theta)$ of at least one unrelated source being located within a certain angular distance Θ from a particular target is given by

$$P(\Sigma,\Theta) = 1 - e^{-\pi\Sigma\Theta^2}.$$

The last column of Table 2 gives the resulting probability for a companion candidate to be unrelated to the primary of a system. Since the 2MASS Point Source Catalog is incomplete for stars fainter than K=14.3, the calculated chance projection probabilities are only lower limits for sources fainter than K=14.3. All companion candidates detected in our survey in binaries have probabilities to be projected unrelated stars well below the percent level. This means that they are very likely bound to their systems, although considering probabilities of individual sources is known to be prone to error (see e.g. Brandner et al. 2000 for a discussion). Five companion candidates in the higher order systems are very likely chance projections, with chance projection probabilities between 2% and 17%. These are

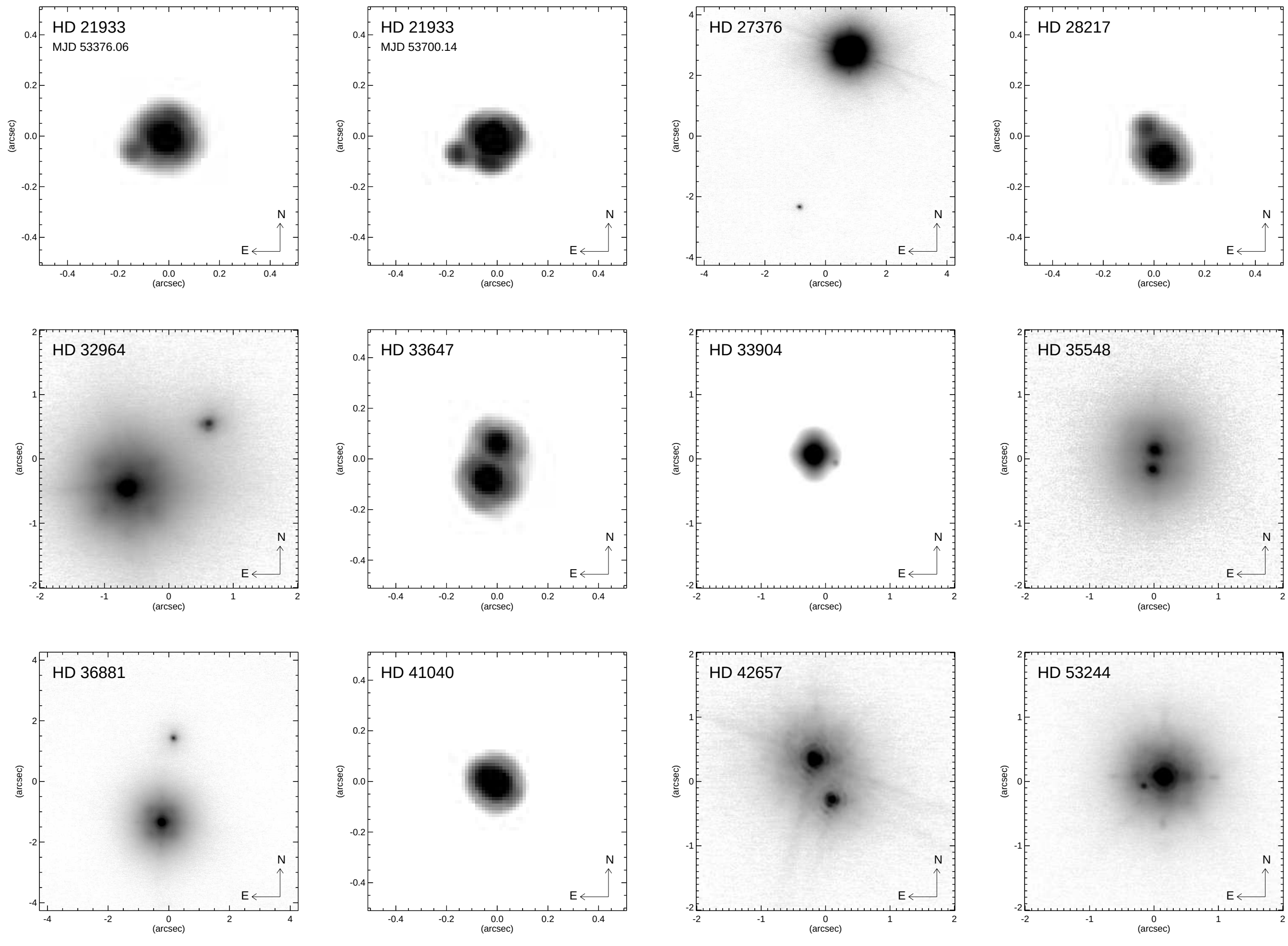

Fig. 1. Images of the binaries detected in our VLT/NACO survey.

HD 158704C, both companion candidates to HD 178965 (B and C), and the two faint companion candidates in the quadruple system HD 66259 (C and D).

4. Discussion

We have announced the detection of 33 companion candidates in 24 binaries, three triples, and one quadruple system. The detected companion candidates have K magnitudes between $5^{\rm m}\!.95$ and $18^{\rm m}\!.07$ and angular separations ranging from $<0.''05$ to $7.''8$, corresponding to linear projected separations of 13.5–1700 AU. The companion candidates around HD 21933, HD 33904, HD 53244, HD 53929, HD 66259, HD 72208, HD 90264, HD 101189, and HD 221507 were detected by us for the first time. Five companion candidates are very likely to be chance projections. In Fig. 5, we show the distribution of the projected linear separations for the studied multiple systems with HgMn primaries. For half of the systems, the projected linear separations are smaller than 100 AU.

In our survey, we found in 28 of the 56 studied systems with a HgMn primary at least one visual companion star, which gives a multiplicity fraction of 50%. This is quite high compared with similar surveys of B type stars. McAlister et al. (1993) studied 211 stars of spectral type B with speckle interferometry at visible wavelengths and obtained a binary fraction of 13.9%. Roberts et al. (2007) studied 70 B stars in the I band with adaptive optics and found 16 companions (of which they concluded that four are not physically bound), leading to a binary fraction $\leq$22.9%. Duchêne et al. (2001) surveyed a sample of 60 OB stars in the NGC 6611 cluster with adaptive optics in the K band and found a binary fraction of 18$\pm$6%, restricting themselves to a separation range of $0.''1$ to $1.''5$, corresponding to 200–3000 AU, a range where less than half of our companions are found. Kouwenhoven et al. (2005) studied the binarity of A and B stars in the OB association Sco OB2 with adaptive optics using a Ks filter. Sixty-five of the 199 stars in their sample have at least one companion, leading to a binary fraction of 32.7%. If one restricts the survey to the 83 B type stars, we find that 23 stars have multiplicity, giving a multiplicity fraction of 27.7%. While our stellar sample is quite heterogeneous in parallax, the parallax of Sco OB2 from their paper (they quote a distance of 130 pc, corresponding to a parallax of 7.7 mas) is quite similar to the average parallax of our sample (7.3$\pm$4.4 mas). The projected linear separations in their sample (29 to 1600 AU) are also quite comparable to ours (13.5 to 1700 AU). Oudmaijer & Parr (2010) observed a sample of 36 B stars and 37 Be stars with NACO on the VLT with exactly the same camera setting as used in our study. The only difference is their use of a narrow-band filter, centered on Brγ, in relation to our

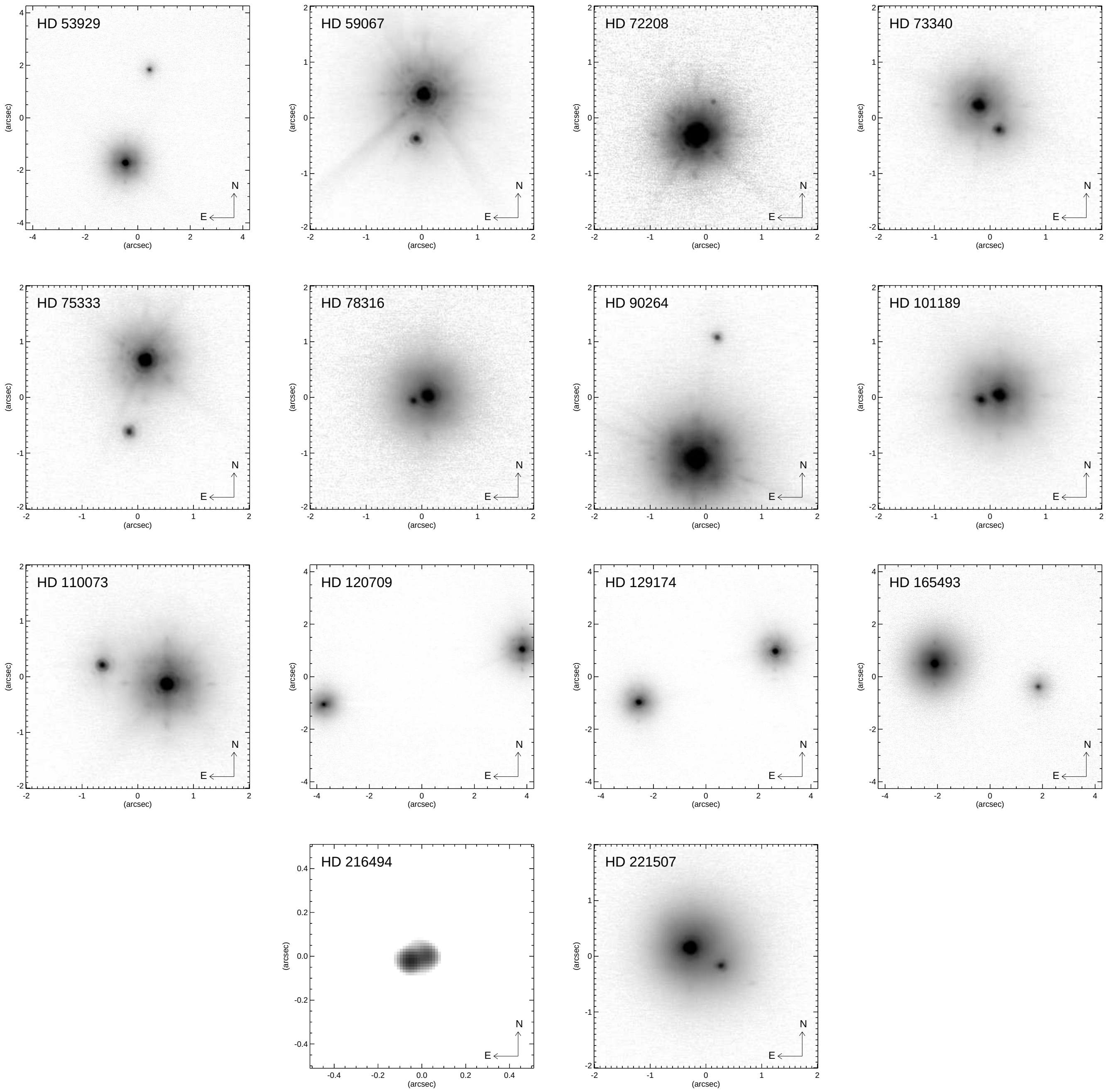

Fig. 1. (continued) Images of the binaries detected in our VLT/NACO survey.

Ks filter. However, their sample is farther away than ours, 4.9±2.7 mas for the B stars and 4.4±2.8 mas for the Be stars. They find 21 binaries (10 for the B stars, 11 for the Be stars), leading to a binary fraction of 28.8%. Compared to these similar studies, our sample contains a significantly higher number of stars harboring a companion.

We note that the inspection of SB systems with a late B-type primary in the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004) indicates a strong correlation between the HgMn peculiarity and membership in a binary system. Among the bright well-studied SB systems with late B-type slowly rotating ($v \sin i < 70\,\mathrm{km\,s^{-1}}$) primaries with an apparent magnitude of up to V≈7 and orbital periods between 3 and 20 days, apart from HD 177863, all 21 systems have a primary with a HgMn peculiarity. Based on this, it cannot be excluded that most late B-type stars formed in binary systems with certain orbital parameters become HgMn stars.

In Table 3, we present the list of the observed HgMn stars with notes about their multiplicity. For each object, we indicate whether it is known to be an SB1 or SB2 and how many astrometric or visual companions are known. A lower case x indicates that there are hints of an SB system, which has not yet been confirmed. Numbers in brackets in the last column indicate objects first found in this study, while underlined numbers indicate objects that we were able to confirm. Of the 56 HgMn stars studied, 32 are confirmed SB systems, 11 are potential SB systems, and

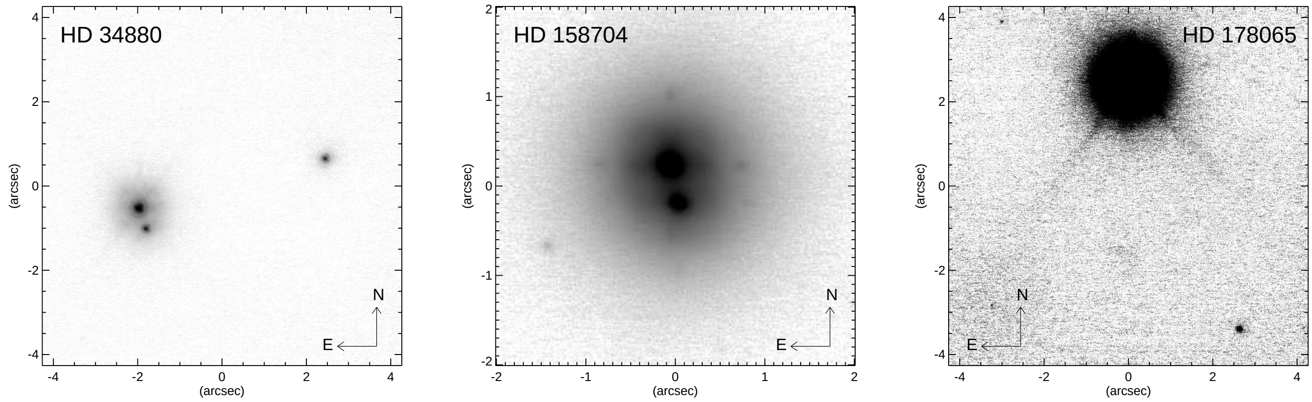

Fig. 2. Images of the triple systems detected in our VLT/NACO survey.

38 have visual companions. Only four of the potential SB systems do not have a visual companion. It is especially intriguing that of the 56 HgMn stars in the sample studied, only five stars, HD 37752, HD 38478, HD 63975, HD 70235, and HD 224926 are not known to belong to a binary or multiple system. This results in a multiplicity rate of 91%.

In the catalogue of multiple stars by Tokovinin (1997), which compiles data on 728 stellar systems of different spectral types, we found four additional multiple systems containing HgMn stars. It is compelling that if the relative frequency of HgMn stars in multiple systems is studied, roughly every third system with a primary in the spectral range between B8 and B9 involves a HgMn star.

The results of our study clearly confirm that HgMn stars are frequently found in binary and multiple systems. However, companionship cannot be established based on K photometry alone, and acquiring data with a near-infrared spectrograph is essential to establish their true companionship. Future spectroscopic observations in the near-infrared should be used to determine the mass of the companions accurately, and explore the physics in their atmospheres by comparing observed and synthetic spectra.

We note that our observations contribute not only to the understanding of the formation mechanism of HgMn stars, but also to the general understanding of B-type star formation. An interesting result about the combination of long- and short-period systems was presented by Tokovinin (2001). He suggested that the fraction of SBs belonging to multiple systems probably depends on the SB periods. It is much higher for close binaries with 1 to 10 day periods than for systems with 10 to 100 day periods. The statistics of multiple systems is still very poor and much work remains to be done. The current survey of binarity and multiplicity of HgMn stars will help us to understand the connection between close binaries and multiplicity, and especially the formation of close binary systems. To find out which role membership of HgMn stars in multiple systems plays in developing their chemical peculiarities, it would be important in the future to compare the ranges of periods, luminosity ratios, and orbital eccentricities, as well as the hierarchy of multiples, with the same characteristics in normal late B systems. In some binary systems with a HgMn primary, the components definitely rotate subsynchronously (Guthrie 1986). It is striking that the majority of these systems have more than two components. Probably the most intriguing and most fundamental question is whether all late-B close binaries with subsynchronously rotating companions belong to more complex systems.

Appendix A: Notes on individual systems

A.1. Systems unresolved in our study

HD 1909: This is an SB2 system with a likely period between 5 and 10 d, according to Wahlgren et al. (2002).

HD 7374: This system is an SB1 with a period of 800.9 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). It is also an astrometric Hipparcos binary according to the CCDM catalogue (Dommanget & Nys 2002).

HD 11753: This system is an SB1 with a period of 41.489 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). It is also an astrometric Hipparcos binary according to the CCDM catalogue (Dommanget & Nys 2002).

HD 14228: This star is a fast rotator ($v \sin i$=240 km s^{-1}; Hutchings et al. 1979), which is atypical for HgMn stars. It is listed in the "Catalogue and Bibliography of Mn-Hg Stars" (Schneider 1981). The Washington Double Star Catalogue (Mason et al. 2001b) lists a companion at a distance of 90″.

HD 19400: Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 0.″1 and a position angle of 179°.

HD 23950: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system.

HD 27295: This system is an SB1 with a period of 4.4521 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004).

HD 29589: Stickland & Weatherby (1984) find hints that HD 29589 is an SB1 system. Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=17.3 at a distance of 10.″00 and a position angle of 251.3°. This companion is very likely outside of our effective field-of-view.

HD 31373: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system.

HD 34364: This system is an SB2 with a period of 4.1346 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic

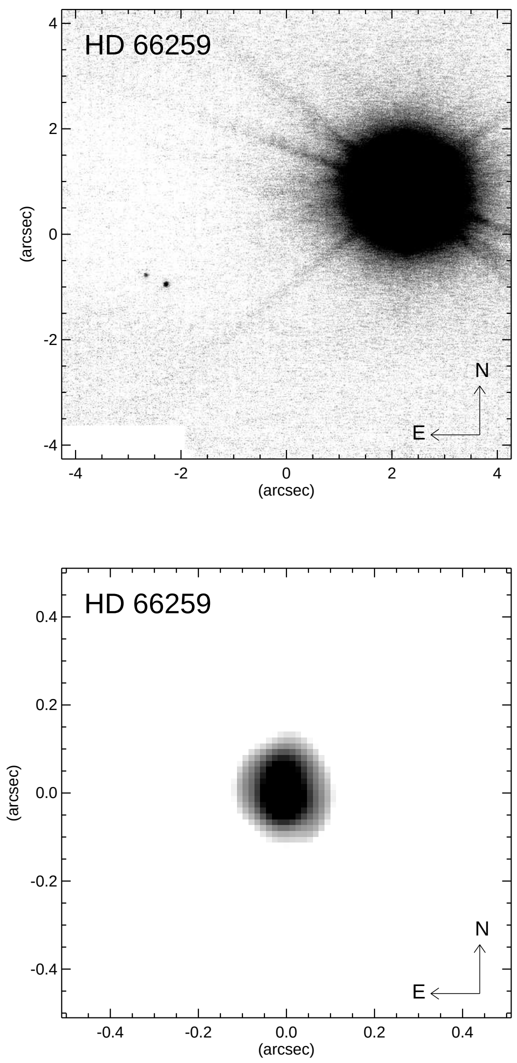

Fig. 3. Images of the wide pair (top) and the close pair (bottom) of the quadruple system detected in our VLT/NACO survey.

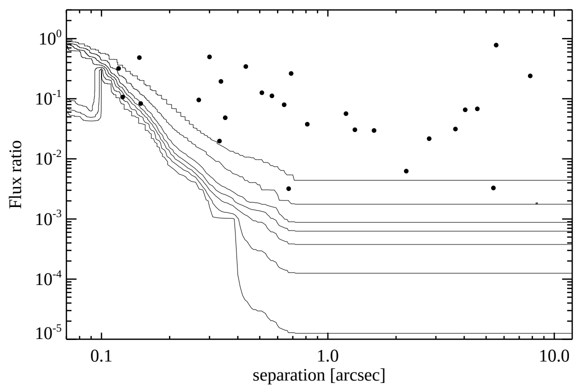

Fig. 4. Completeness map for our survey. The lines represent the completeness of our observations as derived from the sensitivity limit for undetected companions (see Sect. 3.1). The lines are, from top to bottom, 99%, 90%, 70%, 50%, 30%, 10%, and 1% completeness. The circles represent the binaries found in our study.

Table 3. Overview of the known multiplicity of the objects studied in this article.

HD	SB1	SB2	Astrometric or Visual
1909		X	
7374	X		1
11753	X		1
14228			1
19400			1
21933	x		<1>
23950	x		
27295	X		
27376		X	2+1
28217	X		1
29589	x		1
31373	x		
32964		X	1+1
33647		X	1
33904			<1>
34364		X[a]	
34880		X	2
35548		X	1[b]
36881	X		1
37752			
38478			
42657	x		1+1
49606	X		1
51688	x		1
53244	x		<1>
53929	x		<1>
59067			3+1
63975			
65949	X		
65950	X		
66259	X		<1>
66409	X		1
68099	x		
68826		XX[d]	
70235			
71066		x	3
71833			1
72208	X		<1>
73340			1
75333	X		1+1[e]
78316	X		1
90264	X		<1>
101189			<1>
110073	X		1
120709	X		1
124740		X	
129174	X		1+1
141556	X[a]		
144661	x		
144844		X	1
158704		X	1
165493	X		1
178065		X	
216494		X	1
221507			<1>
224926			
41040	X	X	1[c]

Remarks:
[a]There are hints for a third component in these systems.
[b]The visible component is identical with the SB2 system.
[c]The visible component is identical with the SB1 system.
[d]HD 68826 consists of two SB2 systems.
[e]In fact, we see the two visual components as one.

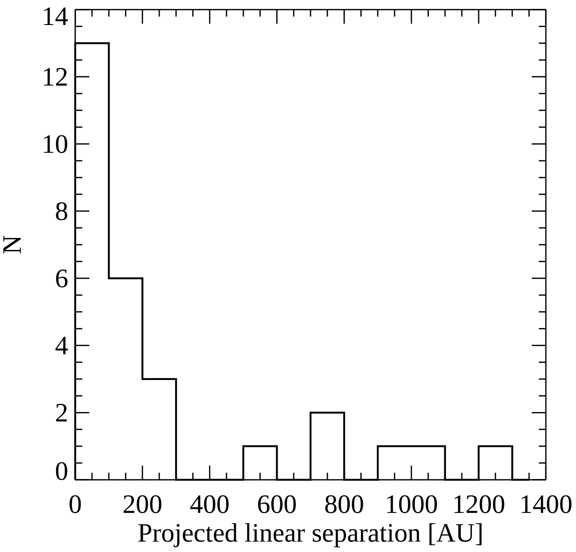

Fig. 5. Distribution of the projected separations of the studied systems with HgMn primaries. For this figure, we removed all companion candidates with chance projection probabilities larger than 1%.

Binary Orbits (Pourbaix et al. 2004). Chochol et al. (1988) discovered a third body in the system. The existence of the as yet unseen third star with a mass of at least 0.51 $M_{\odot}$ was inferred from a light-time effect in the observed minima with a period of 25–27 yr.

HD 37752: There are no references in the literature that indicate multiplicity for this object.

HD 38478: There are no references in the literature that indicate multiplicity for this object.

HD 49606: Stickland & Weatherby (1984) find that HD 49606 is an SB1 system. An optical component of magnitude 13.3 at a distance of 27.″5 is mentioned by Lindroos (1985).

HD 51688: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system. Hartkopf et al. (1997) found a companion on date 1995.3185 at a separation of roughly 0.″1 and a position angle of 68.6°. We did not detect this companion.

HD 63975: There are no references in the literature that indicate multiplicity for this object.

HD 65949: Schneider (1981) lists HD 65949 as an SB1 system.

HD 65950: Abt et al. (1972) found variations in the radial velocity of HD 65950 and classified it as an SB1 system.

HD 66409: Schneider (1981) lists HD 66409 as an SB1 system. The Washington Double Star Catalogue (Mason et al. 2001b) lists a companion at a distance of 12.″4. This companion is very likely outside of our effective field-of-view.

HD 68099: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system.

HD 68826: AO Vel (HD 68826) is a quadruple system (González et al. 2006, 2010), which is composed of two SB2 systems. The system AB is eclipsing, consists of two BpSi stars, and has an orbital period of 1.584584 d. The system CD contains two HgMn stars and has an orbital period of 4.15008 d.

HD 70235: There are no references in the literature that indicate multiplicity for this object.

HD 71066: This is a quadruple system, according to the multiple star catalogue of Tokovinin (1997). The brightest component in the system is a potential SB2, with two common proper motion stars at distances of more than 1′ from the primary. The Washington Double Star Catalogue (Mason et al. 2001b) lists another component at a separation of ∼35″ and a position angle of ∼30°.

HD 71833: Gahm et al. (1983) designate a spectral type F2V to a companion at a separation of 18.″9 and V=11.72.

HD 124740: This is an SB2 system, according to Dolk et al. (2003).

HD 141556: This system is an SB2 with a period of 15.2565 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). HD 141556 was studied by Hubrig et al. (2001) with ADONIS and no companion was detected. The system's γ-velocity appears to be variable on a timescale of years, indicating the possible presence of a third body that is invisible spectroscopically (Dworetsky 1972).

HD 144661: Significant radial velocity variations were detected by Levato et al. (1987), indicating that this object is a potential SB1 system.

HD 144844: Schneider (1981) lists HD 144844 as an SB2 system. Our own spectroscopic material also reveals spectral lines of the secondary. The Washington Double Star Catalogue (Mason et al. 2001b) lists a companion at a distance of 2.″4 and a position angle of 117°. We did not detect this companion.

HD 224926: There are no references in the literature that indicate multiplicity for this object.

A.2. Systems resolved in our study

HD 21933: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system. We were able to resolve HD 21933 twice with the newly found companion candidate at a separation of 0.″124 and a position angle of 112.2° on MJD 53376.06 and at a separation of 0.″149 and a position angle of 111.9° on MJD 53700.14.

HD 27376: This system is an SB2 with a period of 5.0105 d, according to the 9$^{\text{th}}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=9.9 at a distance of 5.″32 and a position angle of 162.5°. Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 0.″1. The Washington Double Star Catalogue (Mason et al. 2001b) lists another component at a separation of 49″ and a position angle of 8°. We detect the companion found by Hubrig et al. (2001) with K=10.17 at a separation of 5.″384 and a position angle of 162.2°.

HD 28217: This is a triple system, according to the multiple star catalogue (Tokovinin 1997). The main component is an SB1, with a third component 0.″4 away from the primary. The inner orbit has a period of 20.438 d and the outer orbit of ∼170 yr. Olevic & Cvetkovic (2005) communicated an orbital solution for the outer system. The companion is

to be expected on the date of our observations at a separation of 0.″104 and a position angle of 359.6°. We detect this companion at a separation of 0.″119 and a position angle of 27.3°; this disagrees with the orbital solution, which needs to be improved.

HD 32964: This is a triple system, according to the multiple star catalogue (Tokovinin 1997). The inner system is an SB2 with a period of 5.5227 d. The third component is a faint (V=10.8) star 53″ away from the primary. Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=9.38 at a distance of 1.″613 and a position angle of 232.6°. We detect this companion with K=9.05 at a separation of 1.″599 and a position angle of 308.3°. Observations in the near future will determine an orbital solution for this fast moving object.

HD 33647: This is a triple system, according to the Multiple star catalogue (Tokovinin 1997). The inner system is an SB2 with a period of 25.365 d. The third component in the system is at a separation of 0.″109 and has an orbital period of ∼120 yr. Andrade (2004) communicated an orbital solution for the outer system. The companion is expected on the date of our observations to be at a separation of 0.″145 and a position angle of 346.1°. We detect this companion at a separation of 0.″147 and a position angle of 345.1°.

HD 33904: Hubrig et al. (2001) studied HD 33904 with ADONIS and did not detect a companion. High spatial resolution X-ray observations of this star revealed that the detected X-rays do not originate in the B star itself, but rather a previously unresolved companion (Behar et al. 2004). Our observations are the first direct detection of a close companion candidate, which we find at a separation of 0.″352 and a position angle of 250.9°.

HD 34880: Stickland & Weatherby (1984) find that HD 34880 is an SB2 system. Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 0.″5 and a position angle of 196° and an additional companion at a separation of 4.″4 and a position angle of 285°. We detect both companions, one at a separation of 0.″511 and a position angle of 199.6° and the other at a separation of 4.″571 and a position angle of 284.9°.

HD 35548: This is an SB2 system, according to Dolk et al. (2003). Novakovic (2007) communicated an orbital solution for this system. The companion is expected on the date of our observations to be at a separation of 0.″292 and a position angle of 174.1°. We detect the companion at a separation of 0.″300 and a position angle of 174.1°.

HD 36881: This system is an SB1 with a period of 1857 d, according to the 9$^{\rm th}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 2.″9 and a position angle of 351°. We detect this companion at a separation of 2.″801 and a position angle of 351.9°.

HD 41040: Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 0.″1 and a position angle of 65°. The inner component is an SB2 with a period of 14.57213 d, the wider component an SB1 system with a period of 12.98 yr, which is also visually separated. Mason et al. (1997) give an orbital solution for the outer system. The companion is to be expected on the date of our observations at a separation of 0.″055 and a position angle of 59.7°. Scarfe et al. (2000) give another orbital solution for the outer system. The companion is to be expected on the date of our observations at a separation of 0.″048 and a position angle of 56.5°. We detect the companion to HD 41040 at a separation of less than 0.″050 and a position angle of ∼243°. Since we measure nearly equal brightness for the two components, we have very likely a 180° uncertainty in our measurement.

HD 42657: Aikman (1976) detected small radial velocity variations. Alzner (1998) gives a separation of 202.″8 and a position angle of 5.19° for a wide companion. Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 0.″8 and a position angle of 193°. We detect this companion at a separation of 0.″688 and a position angle of 202.9°. Observations in the near future will determine an orbital solution for this relatively fast moving object.

HD 53244: This star was marked by Renson & Manfroid (2009) as an object with variable radial velocity measurements, i.e. a potential SB1 system. Schneider (1981) also lists HD 53244 as a potential spectroscopic binary. We find a new companion candidate to HD 53244 at a separation of 0.″332 and a position angle of 114.8°.

HD 53929: Radial velocity variations were detected by Zentelis (1983). We find a new companion candidate to HD 53929 at a separation of 3.″659 and a position angle of 345.5°.

HD 59067: McAlister et al. (1993) found a companion on date 1988.1731 at a separation of 0.″799 and a position angle of 169.0°. The Washington Double Star Catalogue (Mason et al. 2001b) lists three more companions between 20″ and 32″. We find the closest companion at a separation of 0.″811 and a position angle of 170.4°.

HD 66259: Abt et al. (1972) found variations in the radial velocity of HD 66259 and classified it as an SB1 system. We find a new companion candidate to HD 66259 at a separation of less than 0.″050 and a position angle of ∼2.5°. The other two sources at a separation of ∼5″ are very likely to be a chance projection, with a chance projection probability slightly higher than 5%.

HD 72208: This system is an SB1 with a period of 22.0116 d, according to the 9$^{\rm th}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). We find a new companion candidate to HD 72208 at a separation of 0.″671 and a position angle of 332.1°.

HD 73340: Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=8.65 at a distance of 0.″604 and a position angle of 221.2°. We detect this companion with K=8.54 at a separation of 0.″566 and a position angle of 219.7°.

HD 75333: This target is an SB1 according to the study of Stickland & Weatherby (1984). Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=9.45 at a distance of 1.″340 and a position angle of 165.8°. In a follow-up campaign at the Keck observatory, Hubrig et al. (2005) resolved the secondary component into another binary. They found a separation of 1.″351 for the wide pair A-B and a separation of about 65±5 milliarcseconds for Ba-Bb. The contrast between A-Ba is about 4.45 mag and between A-Bb about 5 mag. We could not separate the close binary, Ba-Bb, which we detect as one companion with K=9.26 at a separation of 1.″316 and a position angle of 167.5°.

HD 78316: This system is an SB1 with a period of 6.3933 d, according to the 9$^{\rm th}$ Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004). Mason et al. (2001a)

found a companion on Besselian year 1999.1606 at a separation of 0.″286 and a position angle of 108°. This star was also resolved by Roberts et al. (2005) on Besselian year 2003.0077 with a separation of 0.″30 and a position angle of 104°. We find this companion at a separation of 0.″269 and a position angle of 109.7°.

HD 90264: This is an SB1 system, according to Dolk et al. (2003). We find a new companion candidate to HD 90264 at a separation of 2.″219 and a position angle of 350.2°.

HD 101189: There are no references in the literature that indicate multiplicity for this object. We find a new companion candidate to HD 101189 at a separation of 0.″337 and a position angle of 104.1°.

HD 110073: This object is an SB1 system, according to Schneider (1981). Hubrig et al. (2001) studied this system with ADONIS and found a companion of K=7.93 at a distance of 1.″192 and a position angle of 75.0°. We detect this companion with K=7.96 at a separation of 1.″202 and a position angle of 73.9°.

HD 120709: This is a triple system, according to the Multiple star catalogue (Tokovinin 1997). The inner system is an SB1 with a period of 17.428 d. There is a common proper motion object at a distance of 7.″851 and a position angle of 106°. We detect this companion at a separation of 7.″830 and a position angle of 105.5°.

HD 129174: Stickland & Weatherby (1984) find that HD 129174 is an SB1 system. Dommanget & Nys (2002) mention in the CCDM catalogue a nearby component at a separation of 5.″6 and a position angle of 108°. The Washington Double Star Catalogue (Mason et al. 2001b) lists another companion at a separation of 126″. We detect the close companion at a separation of 5.″537 and a position angle of 110.5°.

HD 158704: This is an SB2 system, according to Dolk et al. (2003). Hartkopf et al. (1996) found a companion to HD 158704 at a separation of 0.″352 and a position angle of 11.3° on date 1992.4550. We find this companion to HD 158704 at a separation of 0.″434 and a position angle of 192.9°. The difference in position angle with Hartkopf et al. might be due to a 180° uncertainty in their measurements. Another object at a separation of 1.″637 and a position angle of 123.6° is very likely a chance projection, with a chance projection probability of $\sim$2%.

HD 165493: This is an SB1 system, according to Dolk et al. (2003). Lindroos (1983) gives a separation of 3.″9 for a companion in the system. We detect this companion at a separation of 4.″041 and a position angle of 257.4°.

HD 178065: This target is an SB1 system with an orbital period of 6.87 d according to Guthrie (1984). Dolk et al. (2003) identified HD 178065 as an SB2 system. Mason et al. (1999) list HD 178065 as an unresolved Hipparcos problem star. The two sources found by us close to HD 178065 at 6.″4 and 3.″3 are very likely to be a chance projection, with a chance projection probability of 17%.

HD 216494: This is a triple system, according to the Multiple star catalogue (Tokovinin 1997). The inner system is an SB2 with a period of 3.4298 d. An occulting, visual component on an 18 yr orbit was found at a separation of 0.″078. Mason (1997) communicated an orbital solution for the outer system. The companion is to be expected on the date of our observations at a separation of 0.″080 and a position angle of 288.9°. We detect this companion at a separation of 0.″069 and a position angle of 285.9°.

HD 221507: Hubrig et al. (2001) studied HD 221507 with ADONIS and did not detect a companion. We find a new companion candidate to HD 221507 at a separation of 0.″641 and a position angle of 240.2°.

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